AUSTRALIA

# PRIORITY DOCUMENT

SUBMITTED OR TRANSMITTED IN COMPLIANCE WITH RULE 17.1(a) OR (b)

**Patent Office**
**Canberra**



I, JANENE PEISKER, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. 2002952347 for a patent by EDITH COWAN UNIVERSITY as filed on 30 October 2002.

COMMONWEALTH OF AUSTRALIA
AUSTRALIA
PATENT OFFICE

WITNESS my hand this
Thirteenth day of November 2003

JANENE PEISKER
<u>TEAM LEADER EXAMINATION</u>
<u>SUPPORT AND SALES</u>

ORIGINAL

# AUSTRALIA

*Patents Act 1990*

# PROVISIONAL SPECIFICATION

Invention Title: Optical Amplifier

**The invention is described in the following statement:**

## Optical Amplifier

### Field of the Invention

The present invention relates to an optical amplifier, and, in particular a multi-port optical amplifier using Vertical Cavity Surface Emitting Laser (VCSEL) arrays and other components to provide dynamic pumping. The invention has particular, although not exclusive, utility in optical telecommunications networks, photonic systems, photonic signal processors, and dense optical computer networks.

Throughout the specification, unless the context requires otherwise, the word "comprise" or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

### Background Art

The proceeding discussion of the background art is intended to facilitate an understanding of the present invention only. It should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was part of the common general knowledge in Australia as at the priority date of the application.

Along the path of an optical communication system, optical signals are attenuated by optical fibers and other optical components encountered by those optical signal. Optical amplifiers are key devices within optical communication systems, because their signal amplification is independent of the transmission bit rate and data format.

Semiconductor Optical Amplifiers (SOAs) have the advantage of small size. However, they have several disadvantages, including limited gain and bandwidth, low saturation output power, high noise figure, high nonlinearity, and polarization dependent performance. On the other hand, rare-earth-doped fibre amplifiers, such as erbium doped fibre amplifier (EDFA), can provide gain in excess of 40 dB and low noise figure performance. Their features include very low

polarization sensitivity, high output power (as high as +37 dBm) and wide-bandwidth (up to 80 nm).

A rare-earth doped fibre amplifier operates by the same fundamentals as a laser, which is light amplification by stimulated emission of radiation. The fibre amplifier is driven by another optical source (pump) to excite the active dopant (a rare-earth element) in one of its absorption bands. The electrons in the rare-earth ions are pumped to an exited metastable state. The success of rare-earth-doped fibre amplifiers is mainly due to the long emission lifetime of the metastable state, which permits large population inversions - as almost all ions are in a metastable excited state instead of in the ground state - needed to achieve high gain. Rare-earth doped fibre amplifiers can be used for both the 1.3 μm and 1.55 μm optical telecommunication windows. For example, fluoride fibre, doped with the rare earth element praseodymium, is capable of signal amplification at 1.3 μm, whereas, a silica-based fibre, doped with the rare earth element erbium, is capable of signal amplification at 1.55 μm. Existing silica-based EDFA's require long lengths of few metres for efficient gain performance. High concentration erbium-doped phosphate glasses have recently emerged, which can miniaturize the optical amplifiers to such an extent that planar waveguide technology is possible. With the new glass composition, a waveguide of a few centimeters can achieve signal amplification of the same order of magnitude as current amplifiers with a length of about 10 metres.

Future dynamic optical networks will comprise many nodes linked by a number of different fibre optic links for the transport of optical signals there between. In a dynamic optical network, where each signal might be routed through a different group of optical components, a different amount of attenuation is experienced by each signal component. In order to overcome this problem there is a need for a means to cost-effectively and independently amplify optical signals arriving at a node in the multi-port network.

## Disclosure of the Invention

According to the present invention, there is provided an amplifier of input optical signals, the amplifier comprising:

input means for receiving input optical signals;

beam generating means for generating pump beams;

waveguide means for receiving the optical signals from the input means, and pump beams from the beam generating means, the waveguide means being arranged to absorb the received pump beams and operable to amplify the received optical signal using stimulated emission of radiation, the pump beams being used to drive the waveguide means to provide the stimulated emission, wherein the beam generating means is a vertical cavity surface emitting laser.

Preferably, the amplifier further comprises routing means for receiving the input optical signals from the input means, and pump beams from the beam generating means, and for routing the received input optical signals and the pump beams to the waveguide means.

Preferably, the routing means comprises a glass or sapphire substrate.

Preferably, the routing means includes collimating and focusing means. Preferably, the collimating and focusing means comprise microlens array, or, alternatively, diffractive optical elements

Preferably, the amplifier further comprises monitoring means for monitoring the power of the optical signals and the pump beams. Preferably, the monitoring means is a two-dimensional photodetector array.

Preferably, the vertical cavity surface emitting laser is an integrated circuit, integrated with the photodetector array.

Preferably, the input means has a multi-port configuration, particularly an array of optical fibres.

Preferably, the waveguide means has a multi-port configuration comprising an array of optical fibres.

Preferably, the fibres in the fibre array are either core-pumped or cladding-pumped.

Preferably, the array comprises erbium-doped alumino-silicate fibres, or praseodymium-doped fluoride fibres.

Preferably, the vertical cavity surface emitting laser operates in transverse single-mode. Alternatively, the vertical cavity surface emitting laser operates in multi-mode.

Preferably, the vertical cavity surface emitting laser is arranged with an external cavity resonator.

Preferably, the amplifier further includes a first detecting means for detecting pump beam signals, and a processor to which pump beam monitoring signals are supplied, from the first detecting means, in response to the detected pump signals, the processor being operable to generate control signals for controlling the pump beam generating means, in response to the pump beam monitoring signals.

Preferably, the first detecting means is a photodetector array integrated on a semiconductor chip.

Preferably, the amplifier further includes a second detecting means for detecting the input signal beams, with input monitoring signals being supplied from the second detecting means to the processor in response to detected input signals, the processor being operable to generate control signals for controlling the beam generating means, in response to received input monitoring signals, and pump beam monitoring signals.

Preferably, the second detecting means is a photodetector array.

In accordance with another aspect of the present invention, there is provided a method for controlling the optical gains of an optical amplifier, the amplifier comprising at least one optical fibre amplifier and a pump source, the method comprising the steps of:

measuring the power of pump beams generated by the pump source and deriving a first signal representative thereof;

measuring the power of input optical signals and deriving a second signal representative thereof;

estimating the signal gain based on the measured input signal power and pump power, and deriving a third signal representative of the difference between the measured signal gain and the desired signal gain;

processing the first, second, and third signals to generate a pump source driving current profile in response to the processed first, second and third signals; and

controlling the generation of driving current profile to achieve the desired output power for the pump beam.

This has the advantage of providing an integrated, high-power multi-port optical amplifier structure that uniquely integrates independently controlled pump sources, drive and operational componentry to provide variable optical gain to dynamically compensate for the optical losses in multi-port fibre-optic systems. The invention has a reduced complexity and draws less power than most modern systems.

**Brief Description of the Drawings**

The invention, will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figures 1A and 1B schematically illustrates the concept of rare-earth-doped fibre amplification;

Figure 2 schematically illustrates a multi-port optical amplifier;

Figure 3 schematically illustrates pumping an EDFA using a VCSEL source in accordance with the present invention; and

Figure 4 illustrates a 2D optical amplifier architecture for an amplifier of the present invention.

## Best Mode(s) for Carrying Out the Invention

Throughout the specification, unless the context requires otherwise, the word "comprise" or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

Figures 1A and 1B illustrate the principle of optical amplification in an erbium-doped optical fibre amplifier (EDFA) 1. Figure 1A is a schematic representation of an EDFA, and Figure 1B is an energy level diagram for the EDFA of Figure 1A.

The basic energy diagram of an EDFA is very similar to a 3-level laser system. Supplying photons in a pump wavelength, $\lambda_p$ (usually 980nm), excites the erbium electrons (i.e. increases their energy) to the excitation level. Then the excited electrons undergo a non-emission transition – that is a slight loss of energy - to a metastable level that has a long emission lifetime of approximately 10 ms. Light photons in a signal wavelength, $\lambda_s$ (usually about 1550nm), are amplified by stimulated emissions, and as in a laser, the emitted photons then stimulate other emissions, leading to an exponential growth of signal photons. The long metastable emission lifetime allows high quantum efficiency and low noise figure to be attained. If the metastable emission lifetime were short, then electrons are relaxed too quickly, meaning more photons are spontaneously emitted giving rise to spontaneous noise, and more input pump is needed to keep the electrons in the metastable state.

The EDFA 1 requires a 880nm pump laser 2, a coupler 3, which combines a laser beam from the pump laser 2 with an input signal laser beam 4 into a single

fibre 5, and the EDFA 1, which is the amplification medium. Sometimes, an optical filter (not shown) is used, after the EFDA 1, to filter out the amplified spontaneous noise.

There are several wavelengths that optical fibres can carry. Erbium ions (Er3+) have quantum levels that allow them to be stimulated to emit in the 1550nm band, which is the wavelength of minimum power loss in most silica-based fibres. That gives them the ability to amplify signals in a wavelength where high-quality amplifiers are most needed. EDFA's can be excited by a signal at either 800nm or 980nm, both of which silica-based fiber can carry without great losses, but aren't in the middle of the signal wavelengths. Those wavelengths are also far enough away from the signal wavelength of 1550 nm thus allowing the pump beam and the signal beam 4 to be easily separated. Erbium can also be excited by photons at 1480nm, but this is typically undesirable because both the energy pumping process and the stimulated emission by the signal take place in the same energy band, which causes interactions that lower the efficiency of the EDFA and increase the amplifier noise.

Another important property of erbium for use in an EDFA is that it is fairly soluble in silica, making it easy to dope into mixtures for making silica-based fibres, and by using a co-dopant, such as $Al_2O_3$, $GeO_2$-$Al_2O_3$, or $P_2O_5$, the erbium compound's solubility in the silica mixture can be greatly increased, and some of the EDFA's properties can be improved. For example, GeO2-Al2O3 can be used to almost double the time it takes for excited erbium to relax, which therefore almost doubles the quantum efficiency of the EDFA.

One disadvantage of EDFA's is that their gain varies with a signal's wavelength, which creates problems in many wavelength division multiplexing (WDM) applications. This can be solved by using special optical passive filters that are designed to compensate for the gain variation of the EDFA.

Figure 2 illustrates the basic principle of an optical amplifier 100 of the present invention. In this description, a plurality of inputs and outputs are described –

that is a multi-port amplifier is described. However, it should be noted that this invention applies to single or multiple input and/or single or multiple output systems.

A multi-port optical amplifier 100 comprises an input fibre array 10 for carrying input signal beams, coupled to an input fibre collimator array 11, which converts the input signal beams into collimated beams 12. A VCSEL array 14 generates an array of pump beams 15 perpendicular to the signal beam direction. The pump beams 15 and the collimated signal beams 12 are combined using a WDM beam combiner 13. The combined beams 16 output from the combiner 13 are then coupled into an output array 18 of rare-earth doped fibres via a fibre focuser array 17. The gain of each output port of the fibre array 18 is controlled by the amount of VCSEL pump beam 15 coupled into that particular port. The amount of pump power coupled into an output port can be adjusted by adjusting the current that drives the relevant portion of the VCSEL array 14 associated with that particular output port.

It should also be noted that in free-space multi-port optical processors (e.g. optical switches) the optical signals are inherently converted to free-space beams for parallel processing. After processing, the optical beams undergo different attenuations - which necessitate post optical amplification and equalization. It can be seen from Figure 2 that combiner 13, the VCSEL array 14, and the fibre array 18 can be integrated with a free-space multi-port optical processor to combine the pump beams 15 and the signal beams 12, yielding multi-port amplification as well as gain control (by controlling the power of the VCSEL).

Having described the basic principle of the optical amplifier of the present invention, the concept of pumping an EDFA, using a VCSEL as the pump source will now be discussed, with reference to Figure 3.

As can be seen in Figure 3, a VCSEL 20 is used as a pump. The VCSEL 20 generates a diverging optical beam 21. In practice, the divergence angle is less than 5°. A VCSEL microlens 22 is integrated with the VCSEL 20 to collimate the

VCSEL beam 21. The VCSEL 20 is flip-chip bonded with an Ultra-Thin Semiconductor (UTS) chip 24 that integrates a photodetector monitor 23 to monitor the power of the pump beam from the VCSEL 20. The UTS chip 24 is bonded to a glass substrate 25 whose one edge 29 is cleaved at 45° with respect to the direction of the VCSEL beam 21. This edge 29 allows the VCSEL beam 21 to undergo total internal reflection after being incident on the edge 29. The edge 29 is externally coated with an anti-reflecting coating. The wavelength of the anti-reflecting coating is selected so that a free-space input signal beam 26 incident at the edge 29 from a horizontal direction – that is perpendicular to the VCSEL beam 21 – will pass through into the glass substrate 25 and combine with the VCSEL beam 21. A microlens 27 is etched directly into the glass substrate 25, and its focal length and position optimized, so that the VCSEL beam 21 and an input signal beam 26 into the core of the EDFA 28, wherein the pump beam is absorbed, and the signal beam is amplified.

The VCSEL beam 21 emitting from the VCSEL 20 is efficiently coupled to the doped optical fibre 28. The coupling efficiency of the VCSEL 20 to the EDFA 28 is maximized by optimising the position and the focal length of the integrated VCSEL microlens 22. The coupling efficiency of the input signal beam 26 to the EDFA 28 is maximized by optimising position and focal length of the integrated glass microlens 27.

Several lens manufacturers (e.g. Edmund Scientific, Newport) now offer anti-reflection coating with substantially reduced reflection loss for various wavelengths in optical telecommunications. The EFDA gain is proportional to the amount of pump beam power coupled into the EFDA 24._It is therefore possible to adjust the amount of VCSEL beam 21 coupled into the EDFA 28 so that arbitrary gain is achieved by controlling the amount of pump beam coupled into the EFDA 28. To achieve maximum pumping efficiency, the lengths of the doped fibers are optimized to provide the maximum possible small-signal gain at the maximum available VCSEL pump power. A single VCSEL 20 and EFDA 28 have been described above with respect to Figure 3. However, in a preferred

embodiment of the present invention, a VCSEL array and an EFDA array can be used.

Currently, 980nm VCSEL arrays can generate more than 100 mW of optical power per VCSEL element. For a 64-port doped EFDA fibre array, and 70% pump coupling efficiency, 70 mW of pump power can be coupled into each output port – that is port of the EFDA array. If the length of the doped fibre in the array is optimized and the optical signal power is small (<-10 dBm), more than 13 dBm of output optical signal power can be obtained over the optical telecommunications C band (1530 – 1560 nm). Note that commercially available gain-flattened and gain-clamped EDFA's can be used in the present invention.

As mentioned above, VCSEL and EFDA arrays can be used. Figure 4 illustrates an embodiment of an optical amplifier 100 of the invention using such arrays.

The optical amplifier 100" comprises a 2-D input fibre array 30 with a 2 D input microlens array 31 etched directly into a glass substrate 32 in order to collimate input signal beams 34 from the input fibre array 30. The glass substrate 32 has a V-groove shape 41 with a left edge 33 is cleaved at 45° and coated with an anti-reflective coating to pass a large proportion of the input signal beams 34 through into the glass substrate 32, while reflecting a low-power monitoring signal beam 35 to a flip chip photodetector array 40, for monitoring the input signal beam – as will be discussed in more detail below. The photodetector array 40 is bonded to a UTS chip 60 that integrates a pump photodetector array (not shown) for pump beam power monitoring, and is attached to the glass substrate 32. The right edge 36 of the V-groove 41 is also cleaved at 45°, and perpendicular to the left edge 33. The right edge 36 is also coated with an anti-reflective coating to pass the signal beams 34 through with minimum reflection. The V-groove 41 can be free-space or any index matching glass.

In an alternative, the glass substrate 32 can be replaced by a sapphire substrate. Sapphire has attractive properties that make it a competent material that can be

grown to arbitrary shape: including lens etching with close dimensional tolerances and special surface finishes.

At the output of the glass substrate 32, there is provided a microlens array 37. The microlens array 37 is used focus the signal beams 34 and couple them into the output ports of an EDFA array 38, and is also directly etched onto the glass substrate 32. In an alternative embodiment, the microlens arrays 31, 37 can be replaced by diffractive optical element relays. The EFDA array 38 comprises rare-earth doped fibre collimator waveguides – either erbium-doped alumino-silicate or praseodymium-doped flouride. The fibres can be either core-pumped or cladding-pumped.

A 2-D VCSEL array 50 is used to supply the pump beams 39 for input to various ports of the EFDA array 38. The pitch of the VCSEL array 50, the input microlens array 31, the photodetector array, the output microlens array 37, the input fibre array 30, and the EDFA array 38 must be equal.

The VCSEL array 50 can operate in a transverse single mode, where the EFDA array fibres are core pumped. In an alternative embodiment, the VCSEL array 50 can operate in multi-mode for cladding-pumped EFDA array fibres.

In an alternative embodiment, an external cavity resonator (not shown) can be used in conjunction with the VCSEL array 50 to provide higher effective active diameter and improved loss discrimination between transverse modes.

The detected signal beam and pump beam powers are supplied from the respective photodetector arrays to an electronic processor 46, via a detected signal power bus 42 and a detected pump power bus 44. The processor 46 is operable to estimate the required pump powers - for desired EDFA gains - and to generate the driving currents 48 for the various VCSEL elements of the VCSEL array 50. When the VCSEL array 50 is operated in the active region, the relationship between the output pump power and input driving current is linear. This means that the estimation of the required VCSEL driving current requires one multiplication operation and one addition operation. When the signal power

is small, the EDFA gain can be calculated from the pump power via a simple expression. However, in large-signal regimes, the EDFA gain depends non-linearly on the input signal power as well as the pump beam power. This requires a complex iterative algorithm and a storage medium to accurately estimate the required VCSEL driving current for an EDFA gain target.

In particular, the method for controlling the gains comprises the steps of measuring the power of pump beams generated by the VCSEL array 50 using the photodetector array integrated in the UTS chip 60, and deriving a first signal representative thereof, measuring the power of input optical signals using the photodetector array 40, and deriving a second signal representative thereof. The processor 46 is then operable to estimate the signal gain, based on the measured input signal power and pump power, and to derive a third signal representative of the difference between the measured signal gain and the desired gain. Thus, when there is a difference between the measured signal gain and the desired gain, this value of this representative third signal becomes nonzero, and enables a VCSEL current increment needed to maintain the desired signal gain to be calculated. That is, if the input signal power changes by $\Delta S$, then third signal representative will be the difference between the desired gain and the measured gain, i.e. $\Delta G = G_{desired} - G_{measured}$. The algorithm uses the third signal representative to calculate the corresponding VCSEL current increment, $\Delta I$, necessary to retune the gain to the desired value.

So, the processor 40 is operable to process the first, second and third signals, and to generate a VCSEL array 50 driving current profile in response to the processed first, second and third signals; and, further, to control the generation of driving current profile to achieve the desired output power for the pump beam.

This optical amplifier 100 provides high output power and low noise, making it possible to cascade a multiplicity of optical amplifiers carrying high channel counts at high bit rates. In addition, high-level of electronic and optical integration for efficient automatic gain control via software, can be embedded. A digital control system can be implemented, which features an easy-to-use

interface and command set. Integration of the amplifier is achieved using a standard +5 VDC and GND power lines and a RS-232 interface.

The features and advantages of the multi-port optical amplifier 100 described above can be summarised as follows:

- High port counts: > 64 input/output amplifier ports.
- High gain: > 70 mW of pump power can be coupled into the core of each output doped fibre.
- Low noise figure: The use of appropriate pump wavelengths (980 nm) results in low noise figure.
- Potential of gain flatness: Gain flattening filters can be integrated with the doped fibres to provide flat gain across the entire band.
- Variable gain: The gains of the individual ports can independently be adjusted to support a wide range of fibre span lengths and optical network components losses. The amplifier can be configured via simple software commands – using the method described above
- Signal and pump monitoring: Built-in monitoring can be provided by the bonded photodetector array 40, and the pump beam photodetector array integrated in the UTS chip 60.

Volume production: The amplifier of the present invention is designed for volume production.

Various modifications are possible within the scope of the present invention.

Dated this Thirtieth day of October 2002.

**Edith Cowan University**
Applicant

Wray & Associates
Perth, Western Australia
Patent Attorneys for the Applicant(s)

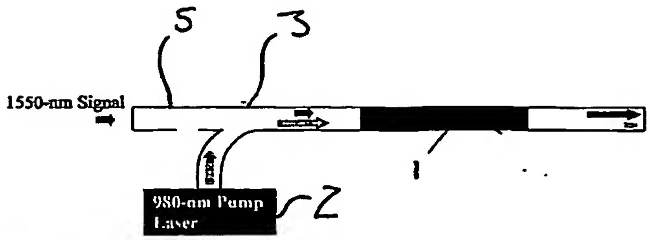
5
3
1550-nm Signal
1
980-nm Pump Laser
2

Fig 1A

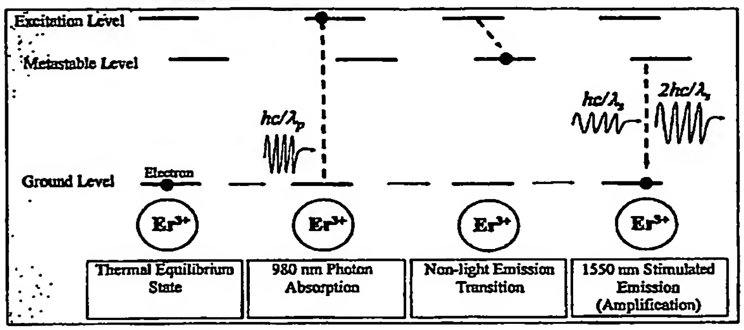
Excitation Level
Metastable Level
Ground Level
Electron
$hc/\lambda_p$
$hc/\lambda_s$
$2hc/\lambda_s$
$Er^{3+}$
$Er^{3+}$
$Er^{3+}$
$Er^{3+}$
Thermal Equilibrium State
980 nm Photon Absorption
Non-light Emission Transition
1550 nm Stimulated Emission (Amplification)

Fig 1B

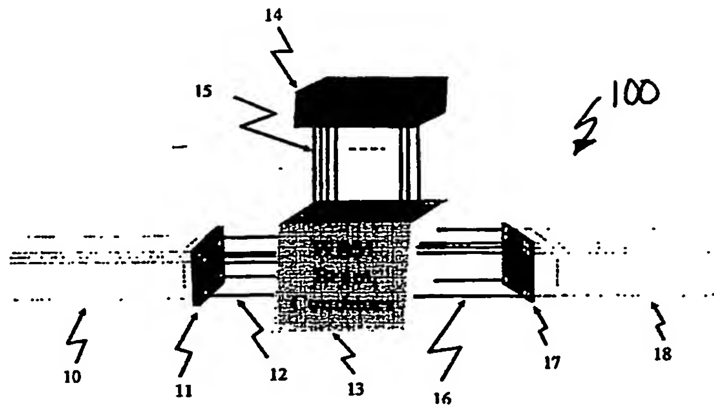


Figure 2

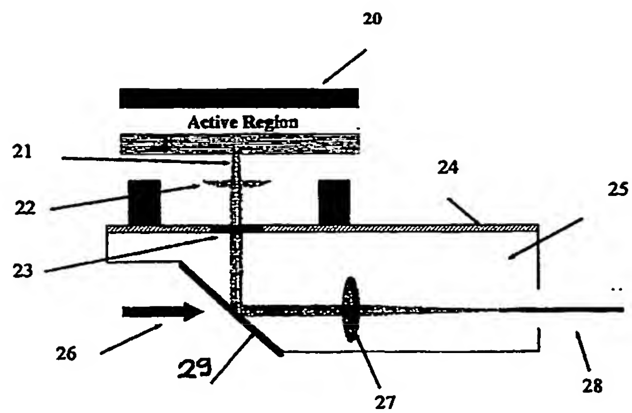


Figure 3

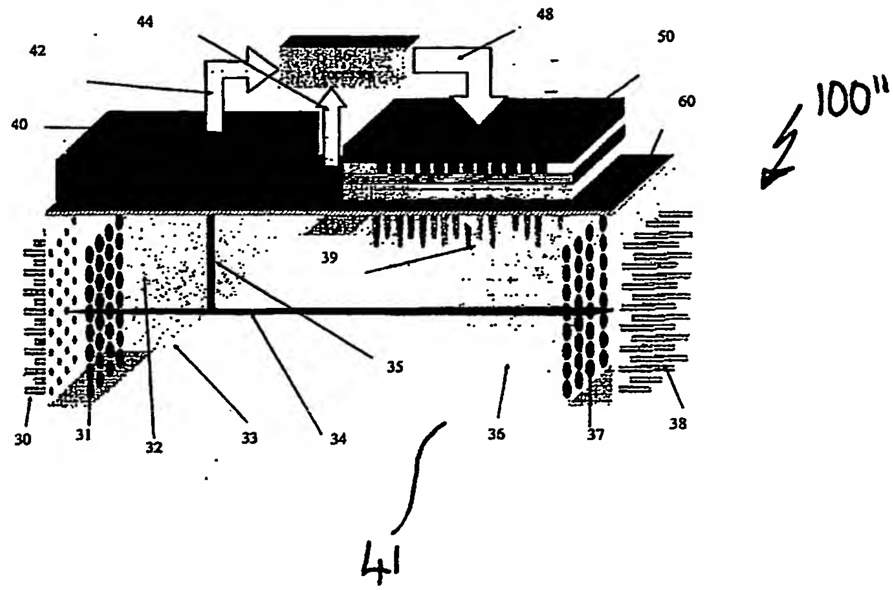


Figure 4

This Page is Inserted by IFW Indexing and Scanning Operations and is not part of the Official Record

# BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☐ BLACK BORDERS
- ☐ IMAGE CUT OFF AT TOP, BOTTOM OR SIDES
- ☐ FADED TEXT OR DRAWING
- ☑ BLURRED OR ILLEGIBLE TEXT OR DRAWING
- ☑ SKEWED/SLANTED IMAGES
- ☐ COLOR OR BLACK AND WHITE PHOTOGRAPHS
- ☐ GRAY SCALE DOCUMENTS
- ☐ LINES OR MARKS ON ORIGINAL DOCUMENT
- ☑ REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY
- ☐ OTHER: ______________________

**IMAGES ARE BEST AVAILABLE COPY.**
**As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.**